FATIGUE LOADS SPECTRA DERIVATION FOR THE SPACE SHUTTLE-SECOND CYCLE

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SUMMARY

Some of the environments and loads experienced by the Space Shuttle or future reusable space vehicles are unique, while others are similar to those encountered by commercial and/or military aircraft.

Prior to the Space Transportation System (STS) flights, fatigue loads spectra were generated for the Space Shuttle based on anticipated environments and assumptions that were shown not to be applicable to the actual flight environments the vehicle experienced. This resulted in the need to generate a new cycle of fatigue loads spectra, which was based on measured flight data as well as mission profiles, reflecting the various types of service and operations the vehicle and payloads experienced.

1. INTRODUCTION

This paper presents the environment fatigue criteria defined for the purpose of deriving the fatigue loads spectra for the Integrated Vehicle Baseline Configuration (IVBC-3) third cycle, the methodology used to generate the fatigue loads spectra for each segment of the flight, and the elements for which the fatigue loads spectra were generated.

1.1 Baseline Vehicle Configuration

The baseline vehicle, also known as Configuration No. 6 Vehicle 6.0, consists of the Orbiter, the External Tank (ET), and two Solid Rocket Boosters (SRBs).

The relative locations of the Orbiter, External Tank and Solid Rocket Boosters are shown in Figure 1. This configuration is pertinent to the pre-launch, liftoff and the initial ascent phases of the Orbital mission. The orbiter vehicle is launched in a vertical attitude by means of the Space Shuttle main engines (SSME) and two SRBs. The orbiter lands horizontally similar to conventional aircraft. The configuration for the descent and landing phase is presented in Figure 2. Figure 3 summarizes a typical sequence of events of the Space Shuttle mission.

The ferry flight from Edwards Air Force Base in California to Florida requires the Orbiter be mated with a Boeing 747 Carrier Aircraft. This mated configuration is shown in Figure 4. It should be noted that an aerodynamically shaped fairing (Tail Cone) is attached to the aft section of the Orbiter in order to reduce base drag and other aerodynamic disturbances during the ferry flight.

*Note: The Ascent segment consists of several sub-segments. They are 4a) Roll Maneuver, 4b) Hi-Q, 4c) Pre-SRB Separation, 4d) Post SRB Staging, 4e) Orbiter Burn Max Load Factor, 4f) Orbiter Main Engine Shut Down, 4g) External Tank Separation, 4h) Orbit Insertion.

2.3.2 Pre-Launch

Pre-Launch is defined as the interval beginning with completion of vehicle transportation and installation on the launch pad and terminating with the commencement of final countdown.

The events that need to be considered for this segment are:

- Wind exposure ET Empty
- Wind exposure ET Full

2.3.3 Buildup And Liftoff

Buildup and liftoff together are the segment usually called liftoff. It begins at first SSME fire, approximately 6.611 sec. before SRB ignition. It continues for 14 seconds, approximately until the beginning of the roll maneuver segment. The dividing line between buildup and liftoff is at 6.5 sec. after SSME ignition. This represents the time just before SRB ignition.

The buildup and liftoff conditions include the effects of the following events:

- Orbiter main engine (SSME) thrust buildup (Symmetric & unsymmetric)
- SRB engines thrust buildup (symmetric & unsymmetric)
- SRB internal pressure buildup
- Wind loads
- Simulated Control system response
- SRB ignition over pressure
- Holddown bolt release

2.3.4 Ascent

Ascent is defined as the interval beginning at the instant of vertical liftoff or holddown release and terminating with the decay of thrust cut-off transients at insertion into orbit for the Orbiter and at SRB separation for the Booster.

The ascent conditions include the effects of the following events:

- Roll Maneuver
- High Dynamic Pressure - Subsonic speed
- High Dynamic Pressure - Supersonic speed
    - Flight Controls (,)
    - High and low performance of SRB's
    - SSME thrust variation
    - Alternate rotational accelerations - pitch, roll, yaw
- Rocket Booster Burn - Max Load Factor
    - High/Low SRB Thrust
- Pre-SRB Staging (Pre-SRB Separation)
    - Heavy/Light ET Configuration

- High/Low SSME Thrust
        - Low/High Orbiter Payload Weight
        - Thrust Mismatch
- Post SRB Separation (Pre-Staging)
    - Heavy/Light ET Configuration
    - High/Low SSME Thrust
    - High/Low SSME Thrust
    - Low/High Orbiter Payload Weight
    - SSME Trim in Pitch and Yaw
- Orbiter End Burn - (Pre ET Separation)
    - High/Low SSME Thrust
    - Low/High Orbiter Payload Weight
    - SSME Trim in Pitch and Yaw
- Orbiter Main Engine Shutdown (MECO)
- External Tank Separation
- Orbital Insertion

2.3.5 Space Operation

Space operation is defined as the interval beginning with the decay of thrust cutoff transients at orbit insertion and terminating with initiation of de-orbit retro impulse. The space operations operation phase includes transfer and mechanical operations in space.

2.3.6 Entry

Entry for the Orbiter is defined as the interval beginning with the initiation of de-orbit retro-impulse and terminating after the transition of the Orbiter to aerodynamically controlled flight. For the booster, it is defined as the interval beginning at the instant of separation from the Orbiter and terminating after the transition of the booster to aerodynamically controlled flight.

2.3.7 Descent And Landing Approach

Descent and Landing Approach (Atmospheric Flight) is defined as the interval beginning with transition of the Orbiter or in the case of the booster to aerodynamically controlled flight and termination at touchdown or splash down respectively.

2.3.8 Landing Impact or Splashdown

Landing Impact for the Orbiter is defined as the interval beginning with the main landing gear touching down on the runway and terminating with the nose gear touchdown. For the Booster splashdown, it is defined as the interval beginning with the initial contact with the water and terminating when the whole Booster is in contact with the water.

2.3.9 Landing Rollout

Landing Rollout is defined as the interval beginning with nose landing gear contact with the runway and terminating with the full stop of the vehicle on the runway.

2.4 Definition Of Ground - Ascent - Orbit Dock Cycle And Deorbit Descent - Ground Cycle

In the case of the Approach and Landing Test and Ferry Flights, the definition of the G-A-G cycle is essentially the same as it is defined for an airplane. However, for the Orbital mission it is necessary to modify the definition of the G-A-G cycle. During the Orbital mission, the Orbiter will experience two equivalent Ground-Air-Ground cycles during a completed Orbital flight. Therefore, the Orbiter will experience two distinct load buildup cycles. These two cycles are identified herein as:
G-A-O/G-A-D cycle or Ground-Ascent-Orbit/Ground-Ascent-Dock Cycle and
D-D-G /U-D-G or De-Orbit-Descent-Ground Cycle/Undock-Descent-Ground Cycle

An aborted mission will experience only one equivalent G-A-G cycle, identified herein as: G-A-G, Ground-Ascent-Ground cycle.

3. ENVIRONMENT

There are three types of environments that need to be considered in the derivation of the fatigue loads spectra for the Space Shuttle Vehicle. Some of these environments are unique to the Space Shuttle and others are similar to those encountered by commercial and/or military aircraft.

The three types of environments are: (1) Natural Environment, (2) Man-made Environment, and (3) Induced Environment.
1. NATURAL ENVIRONMENT - is defined as those external conditions that exist in nature independent of the vehicle. Examples: temperature, pressure, radiation, winds, gusts, precipitation, meteoroids, and dust.
2. MAN-MADE ENVIRONMENT - is defined as those external conditions that are man-made and that exist independent of the vehicle. Examples: sonic booms, explosions, air contaminants, and debris in space.
3. INDUCED ENVIRONMENT - is defined as those conditions created by the vehicle or its systems, or by response of the vehicle to the natural environment. Examples: aerodynamic pressures and forces, aerodynamic heating, rocket exhaust pressures and heating, wind induced bending loads, and differential pressure such as experienced during ascent.

3.1 Wind Definition And Criteria

Ground and in-flight winds and gust are among the natural environments that are considered significant parameters when design and fatigue loads are generated for the Space Shuttle Vehicle structure. Wind design requirements are divided into five separate sets of wind data, each of which corresponds to one of the segments of the orbital and ferry flights. These are winds experienced during (1) On-Pad, Pre-launch, (2) Ascent, (3) Orbiter Entry, Descent and Landing, (4) Ferry Flights, (5) Transportation, and (6) Winds considered for support Facilities. For the purpose of fatigue loads derivation, the above winds are grouped into two categories. They are: (1) Ground Winds data, and (2) In-flight winds data.

1. Ground winds data are defined as those winds which are experienced at heights of 10 to 15 .3 meters (32.8 to 500 ft.) above the ground.
2. In flight winds data are defined as those winds which are experienced at heights of 152.4 meters to 80 kilometers (500 ft to 262,400 ft) above the ground.

Wind design requirements are normally specified in terms of a horizontal wind velocity with an azimuth and with or without gust. Criteria of wind design as defined in Section 5.0 of Reference 1 are applicable for at least one flight of the fatigue life of 100 Orbital flights.

3.1.1 Ground Winds

Ground winds, experienced from various azimuths and acting on the Integrated Space Shuttle vehicle in the fueled and unfilled configurations, are the primary load source when the Shuttle is on the launch pad in the pre-launch condition. The criteria and the number of occurrences of the fueled and unfueled configurations are discussed in Sections 1.6.2.1 through 1.6.2.4 and 4.1 of Reference 3.

3.1.1.1 Ground Winds Used For Pre-Launch IVBC-3 Analysis

To generate the IVBC-3 fatigue loads spectra, measured ground winds at KSC, taken from July 1967 through April 1968, are used. The specifics of the measured data are as follows: The measured wind data (velocity and azimuth) were received from NASA /MSFC . The wind measurements (velocity and azimuth) were taken at 3, 18, 30, 60, 120 and 150 meter elevations. The units of velocity and azimuth were in meters/sec and in degrees, respectively. Measurements were recorded every tenth of a second. A total of 50 measurements, each approximately 10 to 13 minutes long, were analyzed for fatigue analysis. The 18 meter (60 feet) is the reference height at KSC for ground winds; therefore, wind data for each month at 18 meter is used for analysis.

3.1.2 In-Flight Wind

In-flight wind is the largest contributor to structural loads during the first stage of ascent. During the descent phase of the Orbital mission, the wind contributes significantly to structural loads during landing impact.

3.1.2.1 Ascent

Because of the large contribution of the wind to structural loads during the first-stage of ascent, extensive analysis was performed to assess the effects of various wind conditions on the IVBC-3 generic trajectories. A large matrix of synthetic wind cases was run for each of the missions studied. The ascent GN&C trajectory simulation includes a wind model that is capable of generating synthetic wind profiles representing any statistical probability for a given launch month and wind azimuth. Shear buildups of any probability level and different magnitudes of gust were inserted in the probability wind at a specified altitude. The types of synthetic winds used in the IVBC-3 analyses are described in Reference 2 Section 6.3.2, Pages 6-10.

The use of the synthetic winds in combination with gust is not adequate for fatigue analysis for two reasons. First, this approach does not yield a continuous time history of the load response. Second, this approach combines the load due to wind shear and gust, while for fatigue there is a need to have the loads due to wind shear and gust separately, since they are two separate phenomena. The approach taken in fatigue analysis is to consider the load due to wind shear having its own cycle, and the occurrence of the cyclic load due to gust as being superimposed on the load due to wind shear. Therefore, for fatigue analysis, it was necessary to make use of the measured wind profile taken by NASA/MSFC during a period of two years. These measurements were taken at various altitudes for each of the 12 months of the year. NASA provided Rockwell with 1800 measured wind profiles, 150 for each month of the year. These wind measurements consist of both wind velocity and

azimuth. Since 1800 wind cases would be too large of a number to handle and expensive, there was a need to reduce the number of the cases to an acceptable minimum number. The method and procedure used to reduce the number of wind cases to 100 (the number of missions the Space Shuttle Vehicle is certified to) is presented in Section 5.1.4 of Reference 3.

3.2 Gust - Definition And Criteria

Per Reference 5, discrete gusts are specified in an attempt to represent, in a physically reasonable manner, characteristics of small-scale motions associated with vertical wind velocity profiles. Gust structure usually is quite complex and is not always understood. For vehicle design studies, discrete gusts are usually idealized because of their complexity and in order to enhance their utilization.

Gusts may be defined in the form of sharp-edged and repeated sinusoidal waves. They are important types, since they can influence the design of space vehicles. Quasi-square-wave gusts with amplitudes of approximately 9 m/sec have been measured. These gusts are frequently referred to as embedded jets or singularities in the vertical profile. By definition, Reference 5, a gust is a wind speed in excess of the defined steady-state value; therefore, these gusts are employed on top of the steady-state wind profile values. Discrete gusts may vary in length from 60 to 300 meters, thus having different frequencies in addition to varying velocity.

3.2.1 Ground Gust - Velocity and Azimuth

In the present IVBC-3 fatigue analysis a spectrum more representative and reflective of the gust turbulence that the Space Shuttle Vehicle actually sees and responds to was used. Actual measured wind profiles obtained from MSFC for all months of the year were used. These measured winds included gust occurrences. The wind measured profiles were converted into a forcing function and applied to the Vehicle at discrete nodes of the math model ,on the ET, the Orbiter and the SRB/SRM .

The load simulation methodology used to generate the fatigue loads spectra due to the 100 ground wind and gust conditions for the Pre-launch is consistent with that used to generate critical design conditions cases for Pre-launch.

The procedure used to select the segments of the measured winds on each of the components is described in Reference 3 Section 5.1.1and Reference 4. The length of stay on the launch pad for each mission is given in Reference 3 Section 1.3.2.1. The minimum, maximum and average stay on the launch pad are 14, 180 and 47.5 days, respectively.

3.2.2 In-flight Gust - Velocity And Azimuth

In-flight winds were defined in Section 3.1.2. Although the In-Flight winds and gust are treated separately in fatigue, they are, nonetheless, interrelated in that the wind shear is considered as the Quasi-Steady state about which the gust is oscillating.

The aerodynamic loads during ascent flight can be viewed as following one of these general ground rules:

1. Quasi-Steady state and repeatable airloads are due to steering trajectories which program a selected profile of angle of attack in both pitch and yaw planes. Pitch plane program is selected to bias airloads to a favorable range, which involves in a bias to negative angle of attack during the Hi-Q region of Ascent. Yaw steering program is selected to account for

prevailing crosswinds for a given trajectory and minimize excursions of yaw angles of attack due to winds from a nominal trajectory.
2. Random load oscillations due to wind shears (change in wind speed vs. altitude) during Ascent.
3. Random load oscillations due to gusts (abrupt change in wind speed with altitude) during Ascent.

Discrete gusts are a simplified representation of atmospheric turbulence, which can be characterized as a continuous random process. There are two forms of representing atmospheric turbulence:

1. A turbulence spectra for Horizontal flight, such as observed by aircraft.
2. A turbulence spectra for Vertical flight, such as observed by sounding rocket, Jim-Sphere, and Space Shuttle Vehicle.

In this section the latter will be discussed with the procedure followed to generate the gust turbulence velocity and number of occurrences at the mach numbers of interest.

3.2.2.1 Gust Turbulence For Vertically Flying Vehicles

Reference 6, Section 8.4.8, defines the power spectrum recommended for use in elastic body studies for small scale motion by the following expression:

$$E(K) = \frac{683.4\,(4000k)1.62}{1 + 0.0067\,(4000K)^{4.05}}$$

where the spectrum E(K) is defined so that integration over the domain $0<K<a$ yields the variance of the turbulence. In the above equation E(K) is the power spectral density [(M/sec)^2/cycles per Meter] at wave number K (cycles per meter). This function represents the 99 percentile scalar wind spectra for small-scale motions.

The above turbulence spectra were converted to a synthesis of discrete gust exceedance spectra in the following manner:

1. The spectrum (over normalized frequency range of .00001 to .025 cycles/meter) is divided into 7 frequency band widths.
2. The numerical integration of turbulence power spectral density over each frequency band width is carried out to yield increment of variance. The square root of this quantity is calculated and gives the RMS gust velocity over a given frequency band.
3. Distribution of gust cycles, frequency vs. velocity, is assumed to be represented by a normal distribution function.
4.A representative flight path distance of 10.0 km/mission for 100 missions is used as the basis for total number of gust occurrences.
5. Gust occurrences from various frequency bands are superimposed by RSS combination (similar to ground wind turbulence approach for the IVBC-2) and gust velocity exceedance curves are developed in a similar manner.

3.3 Buffeting

Certain flight regimes and configurations will experience buffeting. These effects are accounted for in the derivation of the fatigue loads spectra where they are significant. Buffet load occurrences are assumed to be a function of the component's natural frequency

and the time spent in the buffet environment. The primary components that are subjected to a significant buffet and their natural frequency are:

Vertical Tail $f_n = 3.7$ cps for Mx , $f_n = 8.1$ cps for My
Inboard Elevon $f_n = 10$ cps Outboard Elevon $f_n = 12.5$ cps
Body Flap $f_n = 13.4$ cps
Upper Rudder $f_n = 30.6$ cps Lower Rudder $f_n = 32.8$ cps

3.4 Temperature And Temperature Cycle

The Orbiter undergoes one temperature cycle during the ascent segment of an Orbital mission, one temperature cycle per orbit during space operations, and one temperature cycle during the descent and landing segment of the Orbital mission.

The Orbiter can fly in a number of different modes which affect temperature management. The typical mode is one where the Orbiter rotates for an even exposure to the sun. The most extreme mode is when one side (usually the bottom of the Orbiter) faces the sun during the whole exposed part of the orbit. Temperature measured data is available from STS-1 through STS-5. However stresses due to on-orbit temperature cycles were determined to be negligible.

4 MISSION AND FLIGHT PROFILES

4.1 Orbital Mission Profiles

The launch vehicle configuration and the definition of an Orbital mission are given in sections 1 and 2. Figure 3 illustrates a typical Space Shuttle Vehicle Orbital Mission Profile.

In the fatigue appraisal of commercial and military aircraft, the various types of flight or mission profiles are grouped into several categories based on the aircraft usage. These mission profiles, grouped into several categories, contain rational definitions of airplane loading and usage, such as external/internal store configuration (which may impact the loading on the aircraft) and take-off/landing weights for evaluation of ground handling loads and ground-air-ground load cycles. The flight or mission significant parameters are also defined in order to be able to derive the fatigue loads spectra for each segment of the flight.

A similar approach to commercial and military aircraft was taken in defining the mission profiles of the Space Shuttle Vehicle which are different than those for airplanes. The Space Shuttle Vehicle mission consists of many flight segments which are short in duration.. Furthermore, the significant parameters that affect the load response at each segment are different and in some segments numerous.

In the following paragraphs each segment of the Ascent mission profile is discussed.

4.1.1 Ground Operations

Definition of the events that take place during ground operations are given in section 2.3.1

4.1.2 Prelaunch

The definition of the Prelaunch segment is given in section 2.3 The primary load source for Prelaunch is ground winds from various directions experienced by the Space Shuttle Vehicle (SSV) while it is on the launch pad in the unfueled and fueled configurations. The number of wind velocity occurrences during the unfueled and fueled configurations is based on measurements of ground wind conditions at KSC. Wind exposure is affected by the length of time the Space Shuttle Vehicle is on the launch pad. The length of stay of the Space Shuttle Vehicle on the launch pad is compiled from orbital missions STS-1 through STS-40. There were forty-one shuttle missions from the initial flight of April 12, 1981 through May 24, 1991 when STS-40 was flown.

Figure 7 shows the time on the launch pad for each mission in the order that they were flown. Figure 8 shows the number of Shuttle launches occurring in each month of the year. Figure 9 presents the number of all the 100 launches based on the 41 missions distribution and used in the present analysis.

Figure 10 shows the probability of a stay on the launch pad exceeding a given length of time. This probability is derived from the 41 missions considered in the present analysis. In addition Figure 10 shows an exponential probability curve fitted through the measured data of the number of days stay on the launch pad.

To summarize, the criteria used to define the Pre-launch mission profile, based on analysis of the Shuttle stay on the launch pad for flights STS-1 through STS-40, are as follows:

1. The distribution of the stay on the launch pad in the unfueled condition will correspond to the distribution of stay on the launch pad experienced by STS-1 through STS-40.
2. The total number of days of stay on the launch pad for each month of the year that the SSV is projected to experience in 100 missions is given in Table 1.4.1.2-11 of Reference
3. The length of stay on the launch pad is given in terms of number of days, of hours and of seconds.
3. The fueled configuration is on the launch pad for 10 hrs. per mission or 1000 hrs. per 100 missions. To date, there has been an average of 1.7 tankings per mission. The same was applied in the IVBC-3 analysis, i.e., 1700 hrs. of on-pad exposure in the fueled configuration in 100 missions .

4.1.2.1 Methodology Of Developing Prelaunch Mission Profiles

Prelaunch mission profiles for SRB and Orbiter are constructed with the following parameters:

1. The number of days on launch pad 2. Wind Intensity Distribution Each Month:
3. Distribution of Wind Directions at KSC

Each wind segment was applied from the cardinal directions North (0 degrees), East (90 degrees), and South (180 degrees). (No wind is applied from the west since the service structure was considered to effectively block all wind from that direction.) The occurrences were distributed by direction according to MSFC recommendations.

4.1.3 Liftoff Mission Profile

The load cases used for fatigue liftoff were generated by the same system that is used for Design Certification Review (DCR) and Flight Readiness Review (FRR) liftoff loads

cases. The one hundred basic liftoff cases were defined by randomly deriving values for the input parameters.

The input parameters are as follows:

1. Payload (Model) Effect unpredictable so use all models available and assume equal probability except one zero payload and one 65K payload in 100 missions. (Also, some design cases have P0K or STS61G). 2. SRB Temperature. 3. SSME Thrust. 4. SSME Buildup Time. 5. SSME Thrust Misalignment. 6. SSME Side loads. 7. Flight Control Commands to aero surfaces. Measured data from 10 flights were used. 8. Wind Force of ground wind on structure. Measured wind data chosen by launch month. 9. SRB Thrust Misalignment. Angle from axis of SRB. Direction - equal probability of each possible direction. 10. SRB Thrust Offset distance from center axis of SRB. Direction - equal probability of each possible direction. 11. Mu for SRB Case Growth . 12. SRB Ignition Timing . 13. SRB Thrust Mismatch. Delta thrust between SRB's. 14. SRB Performance . SRB steady state thrust. 15. SRB Ignition Interval between signal to ignite and actual ignition. 16. SRB Rise Rate Slope of SRB thrust rise. 17. SRB Internal Pressure Buildup Profile. Use measured data with an equal probability of each. 18. Over pressure Scale Factor. 19. SRB Over pressure Timing . How shock wave of over pressure rises along vehicle. 20. Bolt Release Timing . 21. Structural Mismatch (Stacking Misalignment). 22. Engine Out (Yes/No) Input to the program since engine-out causes a design case. If an engine is out, randomly determine which one is out. 23. Engine Out Timing.

4.1.4 Roll Maneuver

In establishing the Roll Maneuver mission profile, use was made of the prelaunch and liftoff data. Essentially the significant parameters for the Roll Maneuver are: degree of inclination, payload weight, engine temperature, rotational acceleration, SRB gimbal angle, SRB internal pressure and SRB thrust. The roll maneuver is divided into two segments of load periods. The two time periods considered are different in that certain parameters maximize in each segment. The first segment occurs approximately 7 to 12 seconds at which time maximum negative rotational acceleration about x-axis and maximum SRB gimbal angles are experienced. The second segment occurs approximately 12 to 18 seconds at which time maximum positive rotational acceleration about x-axis, maximum SRB internal pressure and maximum SRB thrust are experienced. Since the variation in the loads experienced by the Space Shuttle Vehicle is not large during roll maneuver, only four cases were generated from trajectories which are considered as representative and were used to construct the 100 mission profiles. All the four cases used have a 65k payload. Three of the cases are trajectories with 28.5 degree inclination and the Propellant Mean Bulk Temperature (PMBT) was nominal, hot and cold. The one case with 57 degree inclination was used with nominal PMBT. The dynamic pressure was constant for both segments of the roll maneuver.

4.1.5 Hi-Q

In establishing the Hi-Q ascent mission profiles, the pre-launch and liftoff data from STS-1 through STS-40 was used to define parameters common to all segments of the orbital missions. In addition to common parameters, there are several other parameters that define the ascent profile segments of the Orbital flight. These are:

1. The Environment - Month of Launch, which defines what measured profiles to use.
2. Mass Properties - Vehicle Gross weight and Model
3. Aerodynamic Pressure Distribution

4. Angle of Inclination
5. Trajectory Data
   a. Dynamic Pressure
   b. Pitch and Yaw Angles
   c. Elevon Deflection Schedule (Inboard and Outboard)
   d. Propulsion (Thrust-SRM, SSME, OMS, RCS)
   e. Gimbal Angles

A discussion on each of the above parameters follows:

1. Environment - The 150 winds measured for each month of the year were used. The 2850 winds for two inclinations 28.5 and 57.0 degrees were used in the TRAKR program to generate the rigid load response . Out of all the TRAKR response cases, 100 cases representing 100 missions were selected to give a desired statistical distribution.
2. Mass Properties - The mass properties used in TRAKR representing the 100 mission profiles are given below for M=0.6 and M=2.20, respectively.
Gross weights at M=0.6
Orbiter G. W. = 255,000 lbs. ET G. W. = 1,913,015 lbs.
SRB/L+R G. W. 1,469,888 lbs. Total G. W. = 3,637,000 lbs.

X c.g . =11.21.8 in Yc.g. = 0.50 in Z c.g. = 380.90 in
Ixx = 11,442,300 lb-sec^2-in Iyy = 86,805,200 lb-sec^2-in Izz = 90,196,200 lb-sec^2-in
Ixy = 55,644 lb-sec^2-in Ixz =2,995,500 lb-sec^2-in Iyz = 18,672 lb-sec^2-in

Gross weight at M = 2.20
Orbiter G. W. = 255,000 lbs. ET G. W. = 965,173 lbs.
SRB/L+R G. W. 1,282,719 lbs. Total G. W. = 2,502,892 lbs.

3. Aerodynamics Pressure Distribution - The IVBC-3 integrated vehicle aerodynamic pressure distribution was used as defined in References 7 through 9.
4. Angle of Inclination - For the present fatigue analysis and definition of the mission profiles, two Inclinations were used, 28.5 and 57 degrees.
5. Trajectory Data - The trajectory data is developed by the Guidance, Navigation, and Control (GN&C) Group, and it is given in the time domain. Each wind profile has its own trajectory, since the program used to generate these trajectories is sensitive to the wind azimuth. The six-degree-of-freedom continuous system modeling program (CAMP) generates high-fidelity ascent trajectories incorporating an accurate representation of GN&C related avionics systems, rigid body equations of motion, vehicle propulsion models, aerodynamic models, mass properties, slosh dynamics, and wind and atmosphere models.

Table 1.4.1.4.2-2 of Reference 3 presents trajectory data for one wind (January Wind No. 1) used in the fatigue analysis for an Inclination of 28.5 degrees. It defines the following parameters at eight mach Numbers, M =0.6, 0.9, 1.05, 1.10, 1.25, 1.40, 1.8 and 2.20.

(a) Dynamic Pressure (PSF), (b) Pitch Angle (, degrees), and Yaw Angle (, degrees);
(c) Elevon Deflections, (degrees) for inboard and outboard elevons.
(d) Propulsion - thrust (lbs) for SSME engines 1, 2, & 3 and RSRB/LSRB engines 4, 5.

The 100 wind cases were selected so that they represent the best statistical representation for derivation of the fatigue loads spectra. Figures 11 and 12 illustrate the distribution of Q-alpha and Q-beta within the squatcheloid envelope for the eight mach numbers.

4.1.6 Post Hi-Q Profile

Post Hi-Q segment of the flight contains the following events:

1. SRB burn - maximum load factor. 2. Pre SRB separation. 3. Post SRB staging. 4. SSME burn - Orbiter maximum load factor. 5. SSME end burn.

Since there is little variation in the post Hi-Q segment of flight , the cases run for design were also used for the fatigue loads spectra evaluation.

SRB Burn - Maximum Load Factor consists of the following configurations:

1. High/low SRB thrust. 2. High/low SSME thrust 3. High/low ET weight. 4. High/low Orbiter weight.

Ten conditions were generated for this flight segment which are repeated 10 times to obtain 100 mission profiles.

Pre SRB Separation - is based upon following configurations:

1. Heavy/light ET configuration. 2. High/low SSME thrust. 3. Low/high Orbiter payload weight. 4. Thrust mismatch (maximum mismatch 710,000 lbs).

Five conditions were generated for the pre SRB separation segment which are sequentially repeated to obtain 100 mission profiles.

Post SRB Separation - is based on the following configuration:

1. Heavy/light ET configuration. 2. High/low SSME thrust. 3. Low/high Orbiter payload weight.

Four conditions were generated for this flight segment which are sequentially repeated to obtain 100 mission profiles.

SSME Burn - Orbiter Maximum Load Factor - the following configurations are considered:

1. High/low SSME thrust. 2. Low/high Orbiter payload weight. 3. SSME trim in pitch and yaw.

Three conditions were generated for the Orbiter maximum burn segment which are repeated sequentially to obtain 100 flight missions.

SSME End Burn - SSME end burn case also consists of the following configuration:

1. High/low SSME thrust. 2. Low/high Orbiter payload weight. 3. SSME trim in pitch and yaw.

Three conditions were generated for the SSME end burn segment which are sequentially repeated to obtain 100 missions.

4.2 Ferry Flight Profiles

Ferry flights of the mated Orbiter/747 CA configuration are performed to transport the Orbiter vehicle and its cargo from the post orbital mission landing site back to the KSC launch site. Occasional flights occur from KSC to the Rockwell plant in Palmdale for scheduled Orbiter maintenance, testing and refurbishing activities. This analysis considers a two hop flight for an Orbiter weight of 220,000 lbs. and a four hop flight for an Orbiter weight of 240,000 lbs.

An aerodynamically shaped tail cone is attached to the aft face of the Orbiter (Figure 4) to reduce the drag caused by the exposed SSME's and to smooth out the airflow to the 747 vertical tail surface. The added weight of the tail cone structure and other ferry flight kit items are slightly offset by the drainage of fluids and removal of personnel and other flight related equipment items. Boeing 747-100 aircraft is used to ferry the Orbiter from landing to launch site. The Orbiter incidence angle relative to the 747 body axis is 3.0 degrees. For all ferry flights, the Orbiter control surfaces are set to zero degrees except the body flap which is deflected - 11.7 degrees. This results in a nested configuration of the body flap with the attached tail cone.

5. METHODOLOGY

The methodology used in generating the fatigue loads spectra for IVBC-3 load cycle differs in a number of ways from the approach used in generating the IVBC-2 load cycle. One of the basic differences, is that the current fatigue loads spectra are generated on the basis of mission profiles and flight-by-flight events. It also reflects actual experience and utilization of the Space Shuttle Vehicle from STS-1 to STS-40, and fatigue load spectra generated reflects future anticipated utilization of the Space Shuttle Vehicle within IVBC-3.

The methodology of generating the fatigue loads spectra for each segment of the orbital flight ascertained the loads being generated by the models, and the definition of the environment, reflect the loads experienced by the Space Shuttle Vehicle.

Figure 13 is a flow chart diagram describing step by step the methodology used in generating the IVBC-3 fatigue loads spectra cases. Figure 14 is a flow chart diagram of the programs used to generate the fatigue loads spectra for the critical locations defined in Reference 3 Section 6.

The first block marked with Roman numeral I and Ia shows the various loads simulation programs available to the user to calculate loads for different segments of the Orbital flight. For example, lift off uses the FORTIE, ULTIMATE, and LIFTOFF programs and for Hi-Q wind shear environment the TRAKR program is used. On the other hand, flight measured data can be used in the fatigue spectra generation process if it is first converted to F-Arrays format, only then can it be handled by subsequent programs in this process. Block II shows the PRERASSP process described in detail in Section 7.2 of Reference 3. The purpose of this program is to pick peaks and valleys of a continuous time history and the time consistent loads or accelerations of the remaining degrees of freedom at each respective structural location. Block III shows the process of storing all peaks and valleys on direct access files for subsequent use in the spectrum generation. Block IV is the SALSA program which links together the peaks and valleys from different segments of flight environments at a specific location on the SRB/SRM or Orbiter. This program is further described in detail in Reference 3 Section 7.4. The output format of this program is described in Reference 3 Section 8.0.

Figure 15 is the Fatigue Loads Process Flow diagram.

6. COMPUTER PROGRAMS USED IN DERIVING FATIGUE LOADS SPECTRA

6.1 RASSP

The Rockwell Automated Stress Spectrum Program (RASSP) was developed to generate load and stress spectra and to perform fatigue and fracture mechanics analysis, primarily on the B1-B Bomber. The RASSP was developed by the El Segundo Division of Rockwell, and modified RASSP to accept the unique parameters and format of the Space Shuttle fatigue loads. Figure 16 is a flow diagram of the spectrum generation portion of RASSP. This figure shows the databases that RASSP accesses in order to generate a fatigue spectrum. During the IVBC-3 Fatigue Loads Analysis it became apparent that RASSP could not track time consistent loads, which were necessary for Fatigue/Fracture Damage Assessment. Because of this requirement to track time consistent loads, a program called Shuttle Automatic Loads Spectra Analyzer was developed to generate the fatigue loads spectra which tracks time consistent loads. SALSA was developed as a spectra generator only. It does not perform the fatigue and fracture analysis that RASSP performs:

1. Fatigue Program (Miner's Rule)
2. Non-linear Fatigue Program (YSAFE)
3. Crack Growth Program (EFFGRO)
4. Crack Growth Program (CRKGRO)

A description of SALSA is found in section 7.4 of Reference 3.

6.2 Prerassp

The PRERASSP program was developed to select load or acceleration peaks and valleys from time histories at selected locations on the Space Shuttle Vehicle (SSV) and the time consistent loads at the other Degrees of Freedom (DOF) at each respective location. This is accomplished by reading ASCENT, TRAKR, LIFTOFF, or F-ARRAY cases, and from this large set of loads/accelerations a smaller subset is selected. The time histories of peaks and valleys are then stored into files which will be stored on direct access files for use by SALSA. Following will be a short description of the inputs to the program and the different run options available to the user.

6.2.1 Prerassp Flow Chart

Shown in Figure 17 is a block diagram of the program PRERASSP and its accompanying routines. The purpose of this diagram is to give the user of this program some knowledge as to how the PRERASSP peak selection routine operates and to give the programmer an idea of where to look in case of future size errors or problems which may arise.

6.2.2 Other Programs

Other programs were developed for the purpose of generating the fatigue loads spectra for the various segments and also for storing the data generated. They are described in detail in Reference 3 section 7.0 .

7.0 CONCLUSIONS

1. The IVBC-3 generated fatigue loads spectra reflect the current usage and utilization of the Space Shuttle.

2. The fatigue environment defined for generating the IVBC-3 fatigue loads spectra reflects that experienced by the Space Shuttle.

3. Based on the discussion of the requirements for time consistent loads and analysis presented in Reference 3 , it would be more efficient for future reusable space vehicles to develop a finite element model and compute the voluminous data generated.

4. One of the main features of the post processing program developed is that it enables the structures engineer to directly read any fatigue spectrum generated into the fracture mechanics analysis program. This feature is discussed and illustrated in Reference 3.

ACKNOWLEDGMENT

The author would like to acknowledge the valuable contribution of Mr. Jack Barneburg of NASA/JSC for his technical review and comments as the Loads and Dynamics Panel Chairman and the team at Rockwell who worked diligently on this task. They are: Judith Goldish, Saroj Gupta, Brent Mann, Perwez Obaid and Rick Stauf.

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2. Structural Design Loads Data Book, Vol. 1, Baseline Vehicle Design Criteria and Missions, Report No. STS85-0169-1, Vol. 1, dated February 1988.

3. STS85-0169-6 Structural Fatigue Loads Spectra Data Book, Vol. 6, ORBITER/RSRB/RSRM dated May 1993.

4. Definition of Prelaunch Wind Environment for Space Shuttle Fatigue Loads Spectra (Paper to be published October 31, 1994)

5. NASA TM 78118, "Terrestrial Environment (Climatic) Criteria Guidelines for use in Aerospace Vehicle Development", dated 1977.

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7. Aerodynamic Design Data Book, Vol. 2, Launch Vehicle, Space Transportation System Division, Rockwell International, SD72-SH-0060-2M, dated August, 1983.

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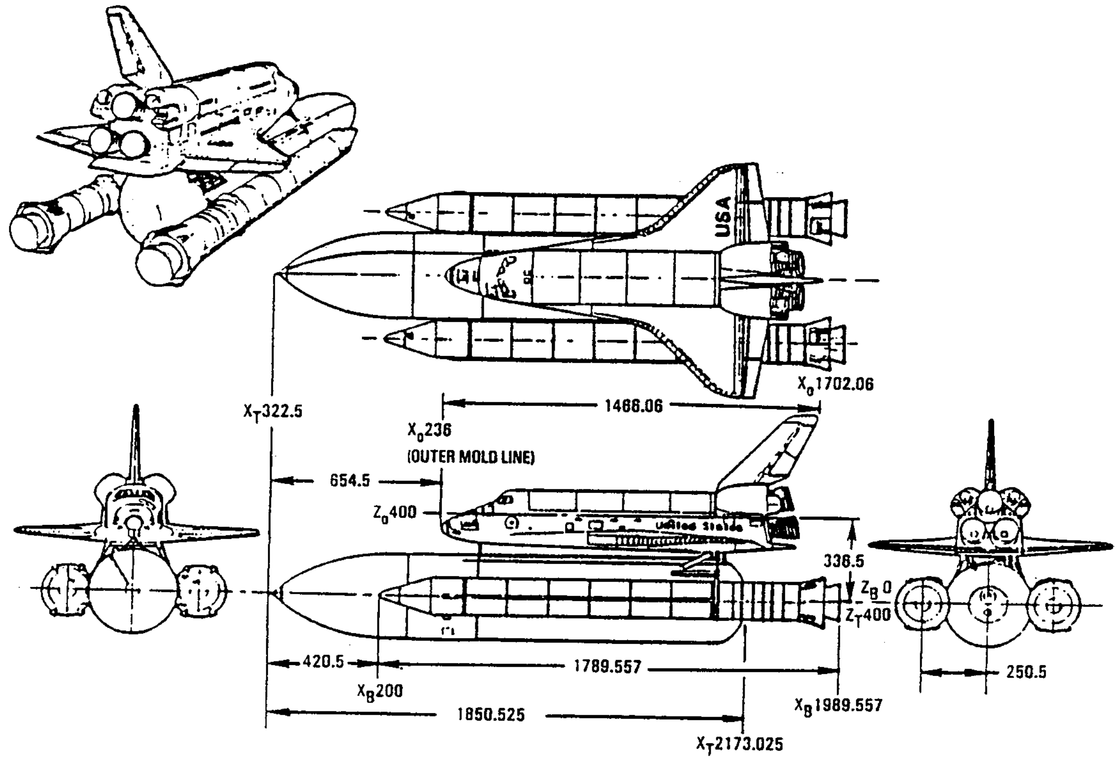
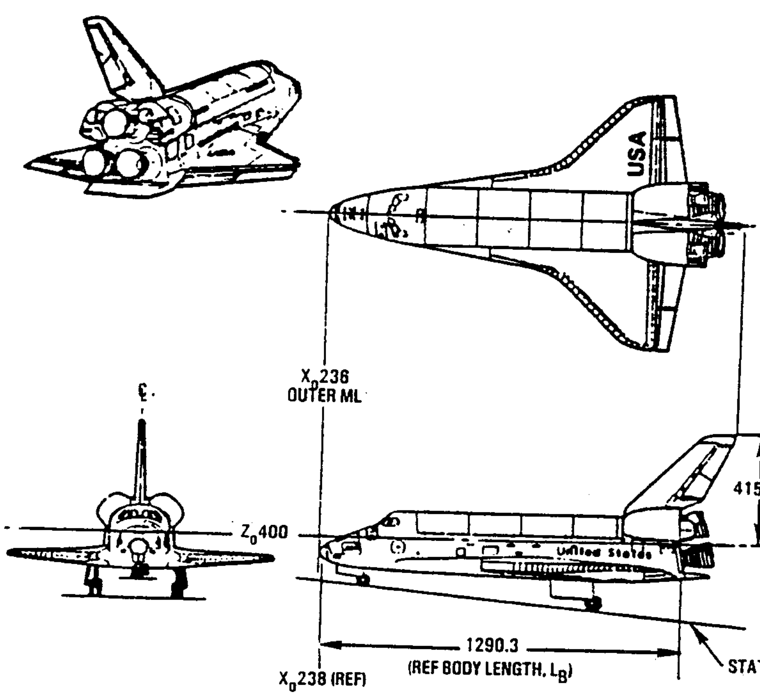
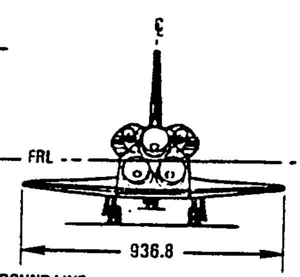
9. Shuttle Operational Data Book, Vol. 1, Johnson Space Center, JSC-08934 dated September 1982.



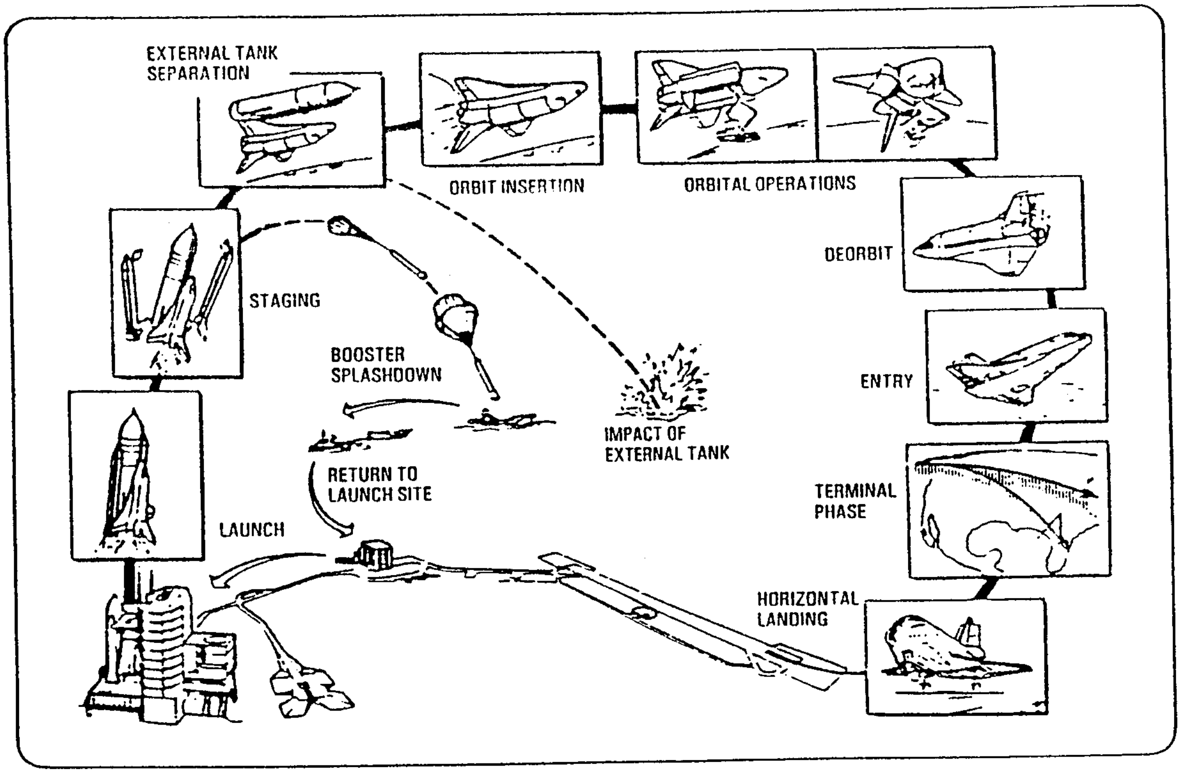
1. Launch Vehicle Geometry



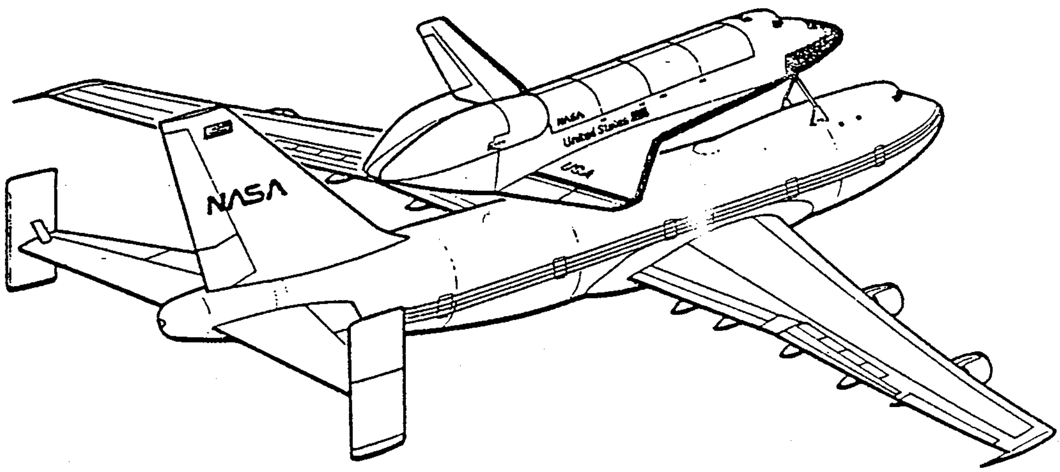


GEOMETRY	COMPONENT	
	WING	VERTICAL
AREA	2690.00 FT^2	413.25 FT^2
SPAN	936.68 IN.	315.72 IN.
ASPECT RATIO	2.265	1.675
TAPER RATIO	0.2	0.404
SWEEP (LE)	45°	45°
DIHEDRAL	3.5°	–
INCIDENCE	0.5°	–
MAC	474.81 IN.	199.81 IN.
CONTROL	**AREA**	**MAX DEFLECTION**
ELEVON (1 SIDE)	206.57 FT^2	-35° TO +20°
RUDDER	97.15 FT^2	±22.8°
SPEEDBRAKE	97.15 FT^2	0° TO 87.2°
BODY FLAP	135.75 FT^2	-11.7° TO +22.55°

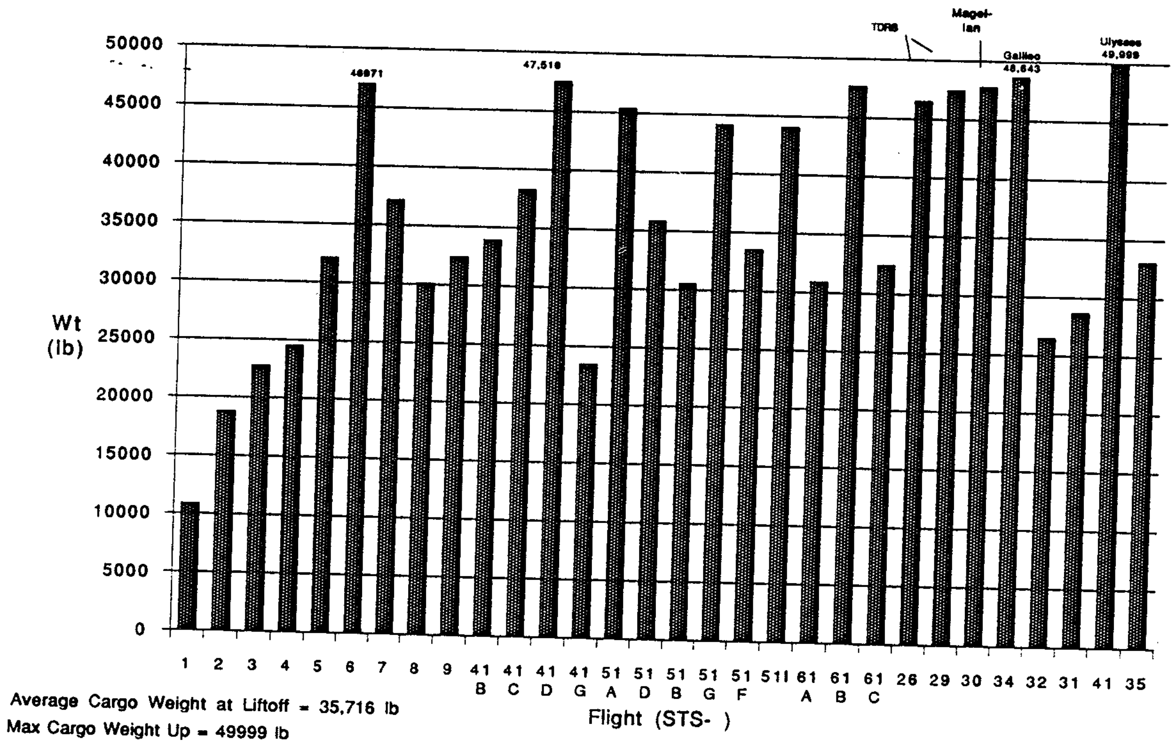
2. Orbiter Geometry



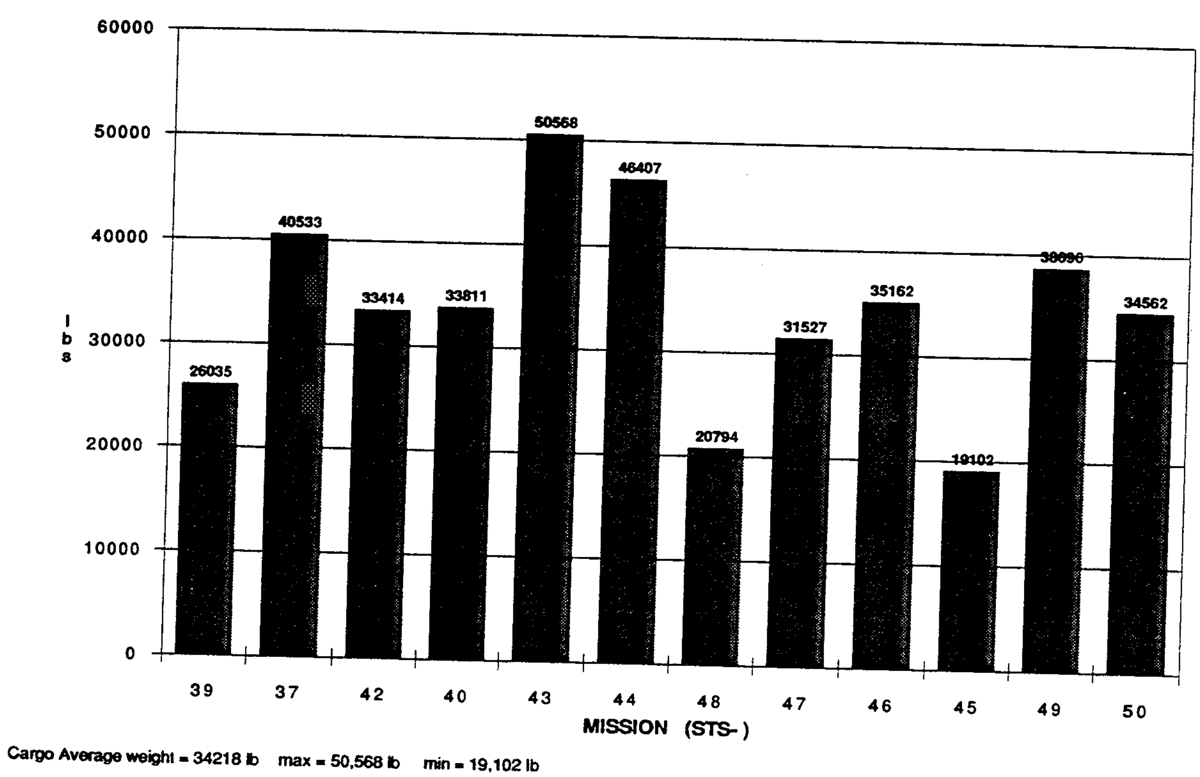
Space Shuttle Mission



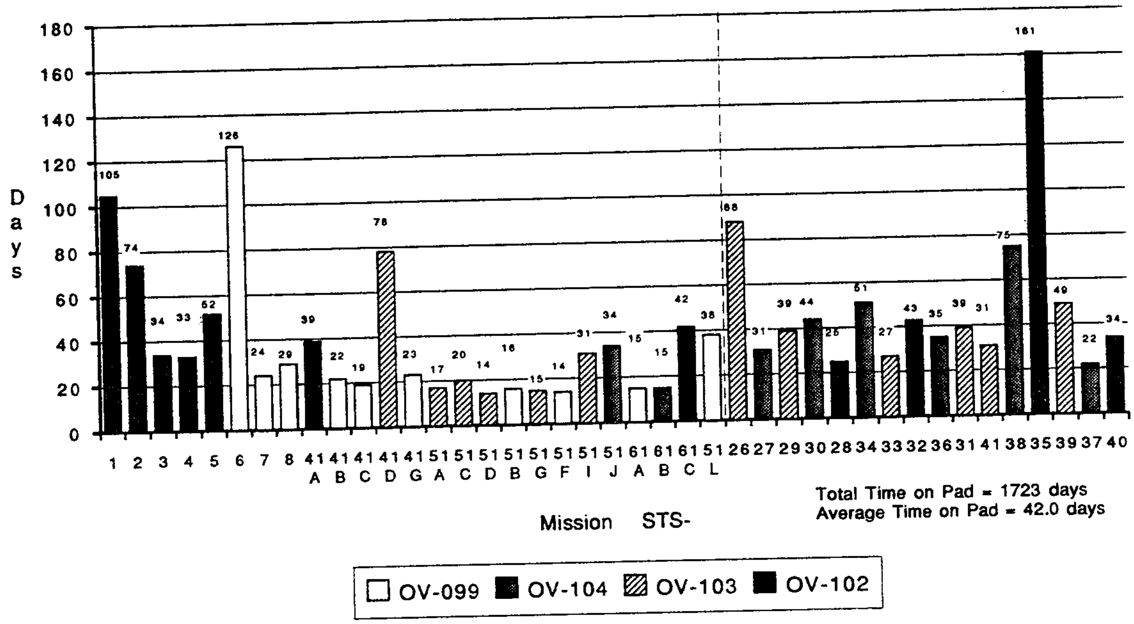
4. Mated Orbiter / 747 Configuration for Ferry Flights



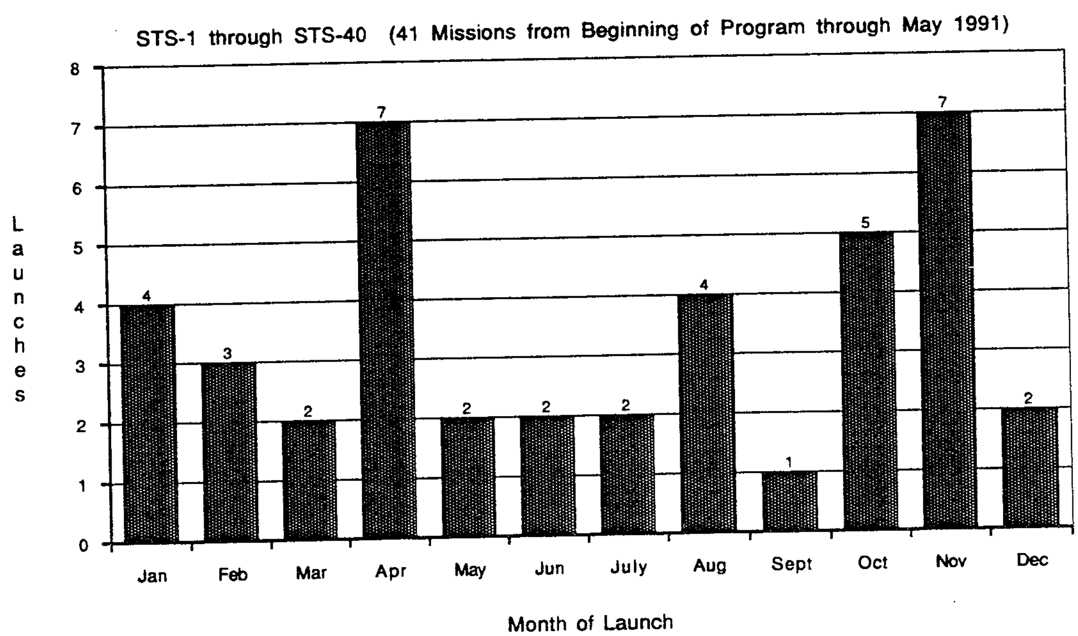
5. Cargo Weight at Liftoff



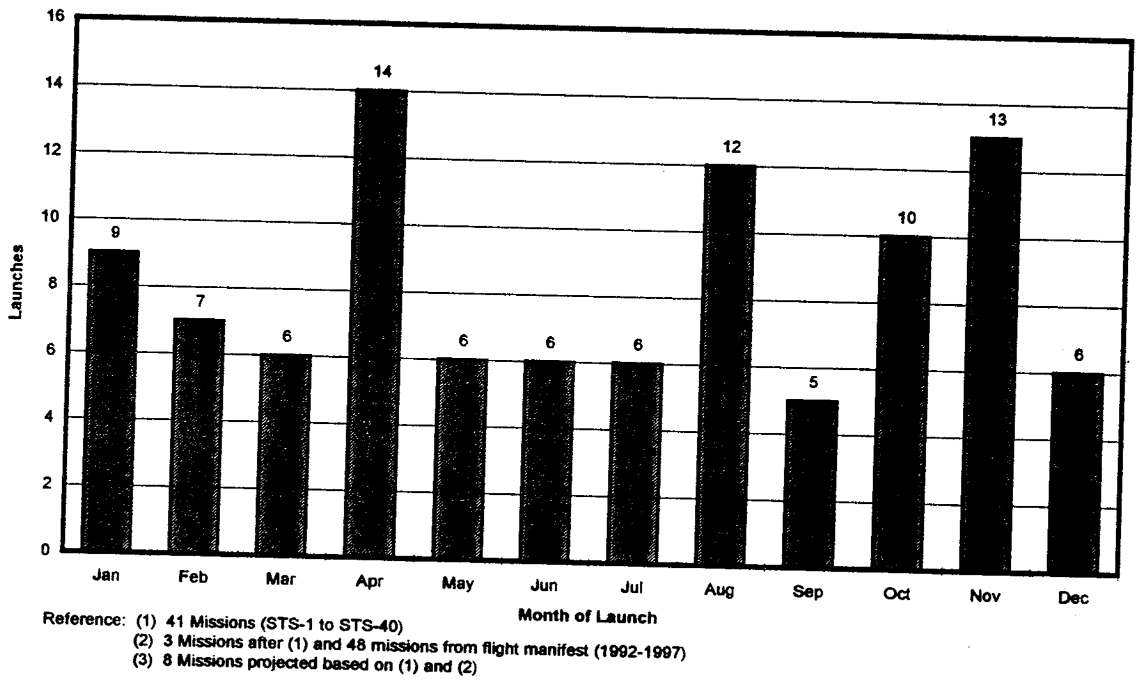
6. Cargo Weight for the Next 12 STS Flights



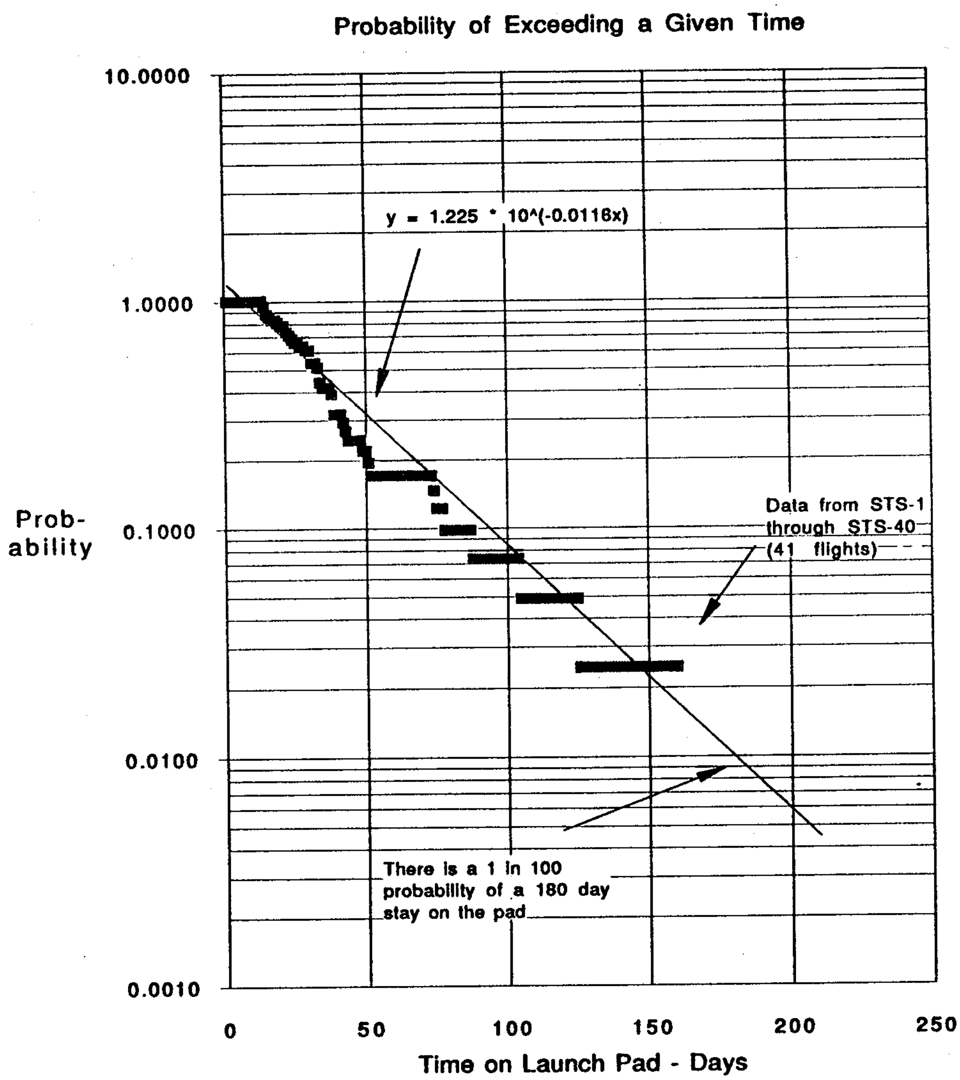
7. Time on Launch Pad for Each Mission



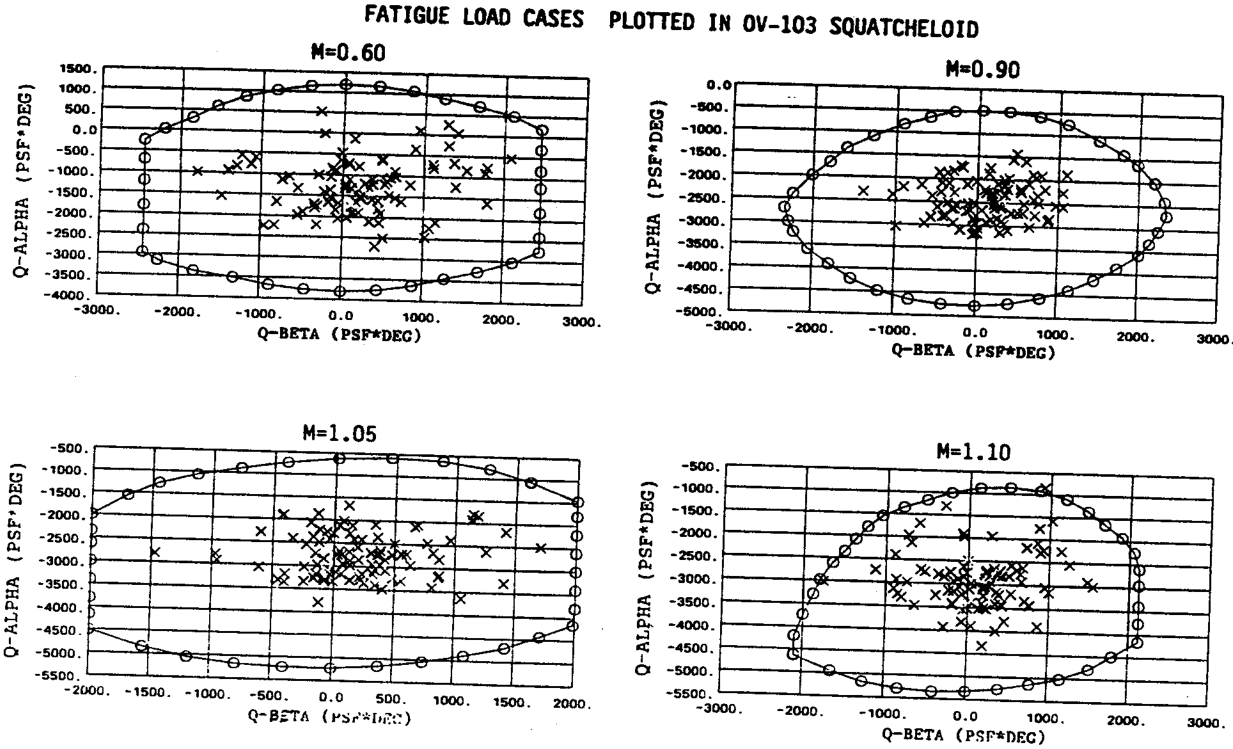
8. Number of Shuttle Launches in Each Month



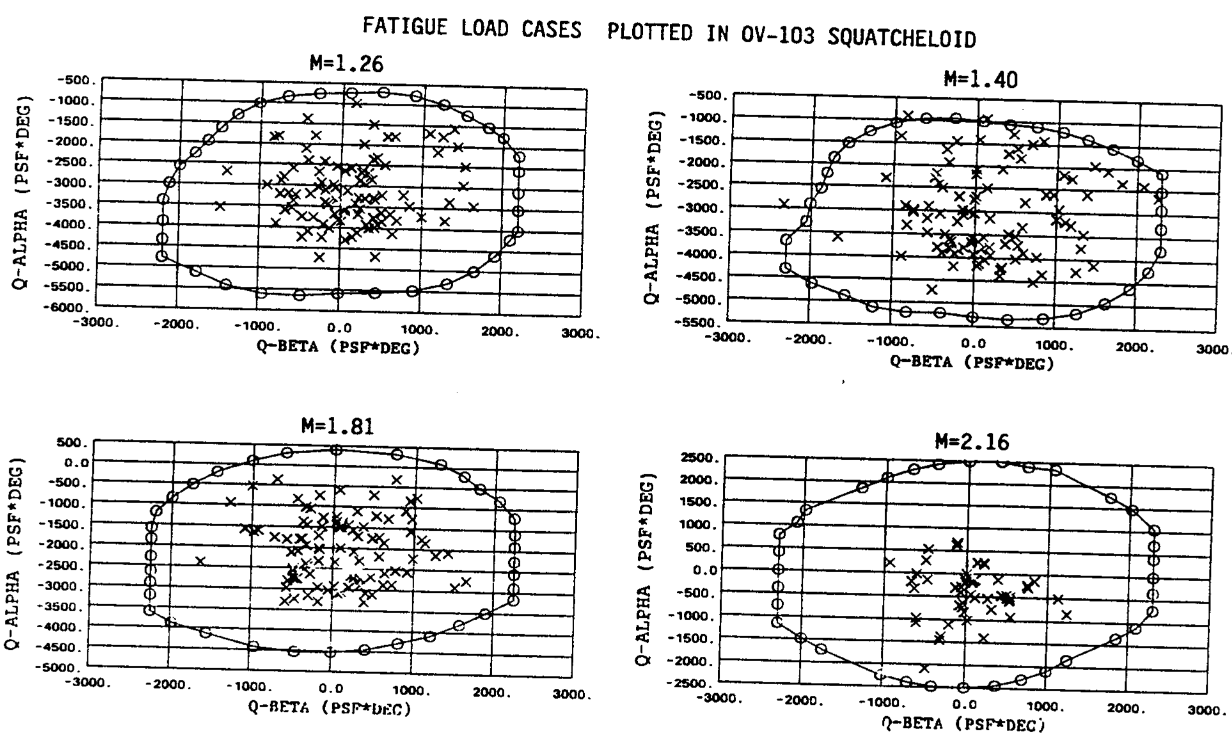
9. Distribution of 100 Missions from KSC



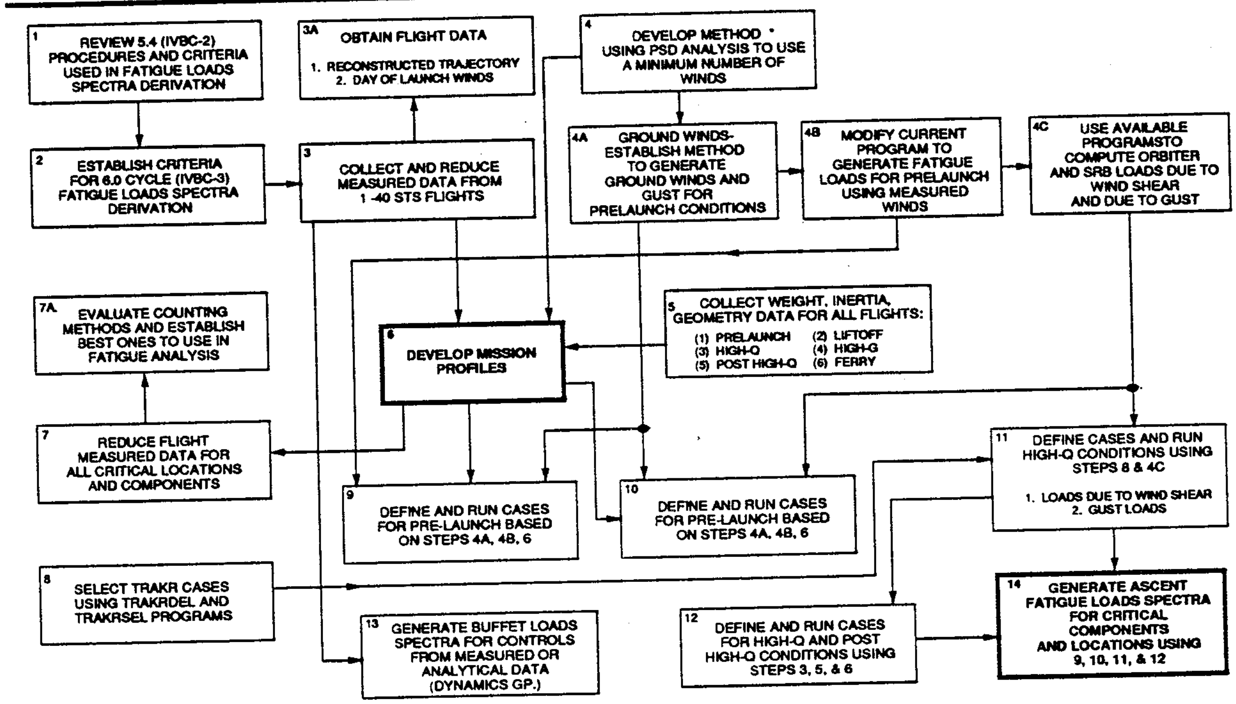
10. Time on Launch Pad



11. Q-alpha & Q-beta Products of 100 selected TRAKR Cases(M=0.6 thru M=1.10)

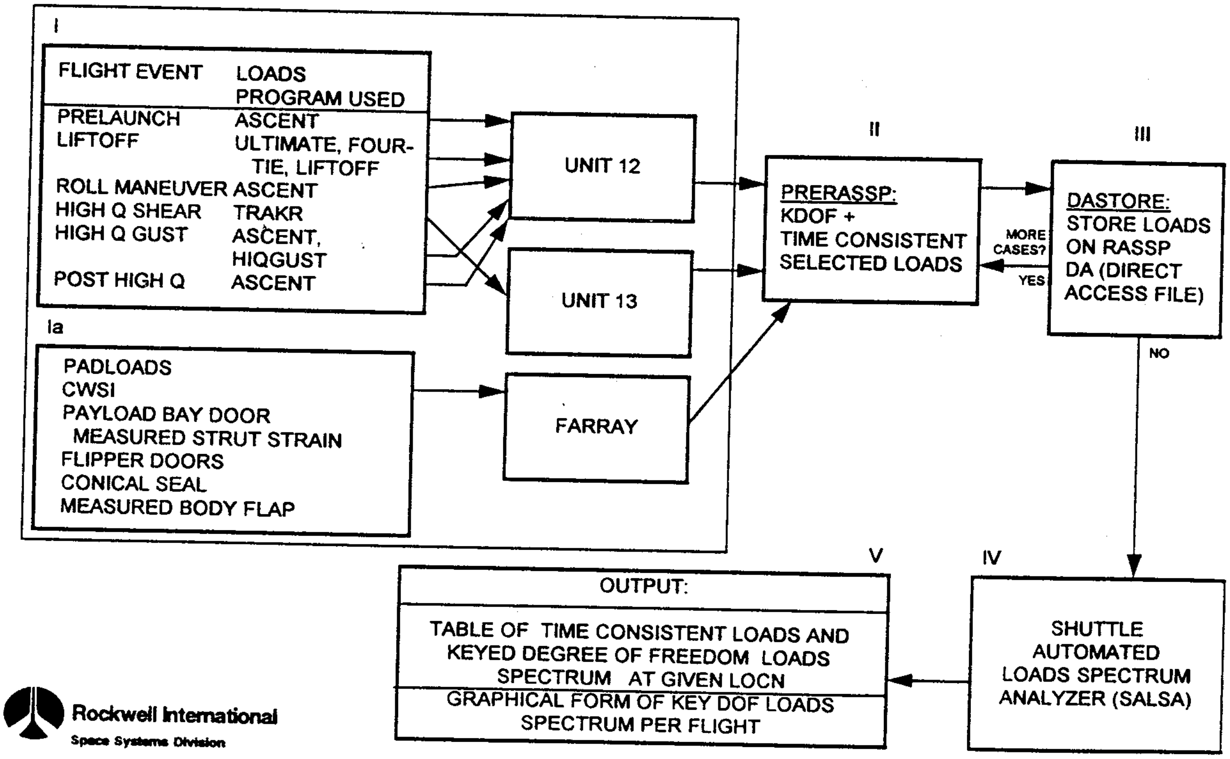


12. Q-alpha & Q-beta Products of 100 selected TRAKR Cases(M=1.26 thru M=2.16)



• METHOD WAS DEVELOPED BUT NOT APPLIED IN THE SELECTION OF THE WINDS HI-Q CASES. METHOD NEED TO BE FURTHER DEVELOPED TO BE APPLICABLE

13. Flow Chart of IVBC-3 Fatigue Loads Spectra Generation



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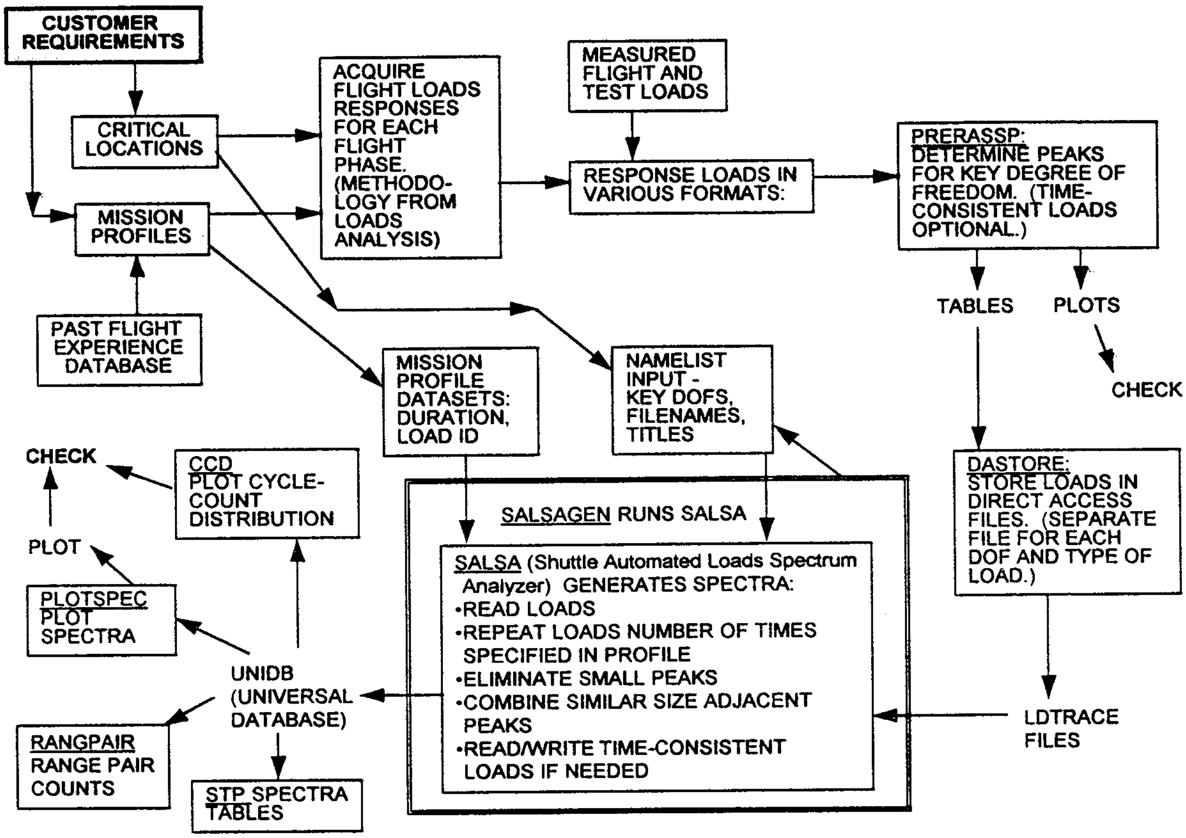
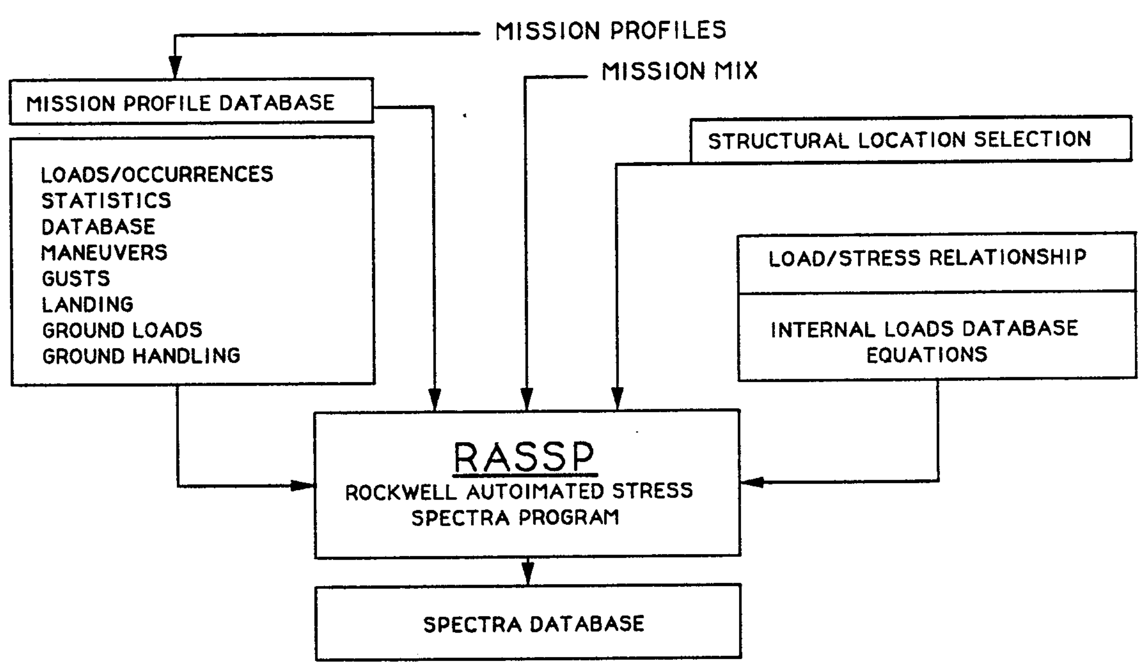
Space Systems Division

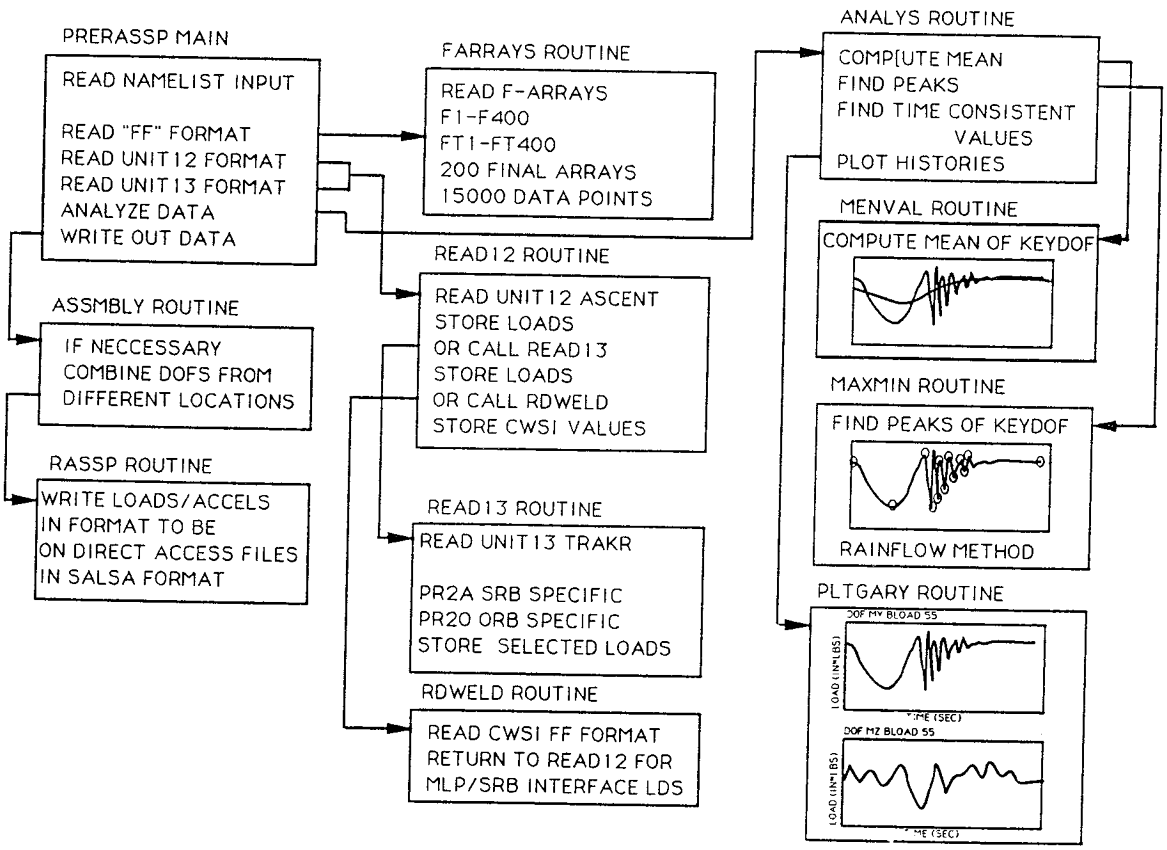
14. Generate Fatigue Loads Spectra Using Following Process



15. Fatigue Loads Process Flow



16. RASSP Fatigue Spectrum Generation Flow Diagram



17. PRERASSP Flow Diagram